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***Economic Tools to Design Efficient Integrated Wildfire  
Fighting Management Strategies***

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# Economic Tools to Design Efficient Integrated Wildfire Fighting Management Strategies

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**Abstract:** In spite of the increasing efforts on behalf of the administrations to meliorate qualitatively the prevention and combat measures undertaken, the wildfire scenario in Mediterranean regions has been worsen and one fears that the situation will be aggravated. Within a backdrop scenario of resource scarcity, huge budget constraints, and other public choices with equivalent priority to that of wildfires prevention and combat, new management wildfire strategies seem to be necessary, to get efficient answers to the increasing complexity of economic and technical Mediterranean forest fires requirements. In this paper, one wants to contribute to clarify how economic tools can we used to improve wildfire management in order to decrease fire risk, within a context of economic scarcity and increasing forest fire risk. We will describe how traditional microeconomic theory of the producer along with linear programming techniques, GIS based data, and computer simulator programs, enables technicians to get the answers to some of the more important questions that rise all along the wildfire process management, and particularly the wildfire combat management.

**Key-Words:** forest fires; combat and prevention; efficient planning; theory of the producer.

## Introduction

Wildfires (a wildfire is a large destructive fire that rapidly spreads out of control, happening most frequently in the summer, when the brush is dry and flames can move unchecked through a wooded area; the fire often begins unnoticed and spreads quickly, lighting brush, trees and homes and it may be started by a campfire that was not doused

properly, a tossed cigarette, burning debris, lightning or arson or other causes) has become in the last decades one of the biggest environmental problems Mediterranean forest is facing. These occurrences are characterized by high levels of destruction of build, natural, and human capital, imposing to Mediterranean society a great financial burden. The nature and virulence of these events and related consequences are forcing the Mediterranean administrations to affect greater amounts of financial, human and material resources to the design and implementation of forest fire prevention and fighting strategies. However, the results seem very far from the objectives traced within the frame of the fire management strategies. Forest wildfires continued to grow in number and extension, and so did the physical and monetary damages, particularly in the first 8 years of the current century (DGRF 2007). In spite of the increasing efforts on behalf of the administrations to meliorate qualitatively the prevention and combat measures undertaken, the wildfire scenario in Mediterranean regions has been worsen and one fears that the situation will be aggravated particularly within the framework of the present climacteric changes. Following this state of the art, one concludes that the methodology commonly used in the design and implementation of wildfire prevention and fighting strategies, seems no longer to be the more adequate. Equally it seems not reasonable or socially efficient, to simply continue to adopt a wildfire prevention and combat management based on the *ad hoc* accruing of financial and other human and material resources, each time the backdrop wildfire scenarios turns worst. Firstly, because wildfires have a strong component of uncertainty which is measured in terms of the probability of ignition and the probability of existing conditions to the development of the fire. Secondly, because there is another important component associated with forest

fires: the heavy damages and level of destruction wildfire enhances (include forest ecosystem destruction and/or damages which implies the loss or damage of the stock of natural capital and of all direct and indirect benefits produced by this type of ecosystems, the destruction and damages over properties and infrastructures, as well as human losses and human health damages, psychological damages supported by the populations, and so on (Weiner 2001, Ramachandran1998). And finally, because the climacteric and social economic conditions that partially explain this type of occurrences in the present will persist and even aggravate in the future. Within a backdrop scenario of resource scarcity, huge budget constraints, and other socio-economic choices with equivalent priority to that of wildfires prevention and combat, new management wildfire strategies are necessary to respond efficiently both from the economic and technical point of view, to the increasing complexity requirements of Mediterranean forest fires.

Till very recently, prevention and combat strategies have been traditionally designed by technicians coming from other scientific areas, different from economics (Riedout and Ziesler 2004). The absence of economic thought within these areas of management has been evidence, particularly till the last century, which can be partially explained by two major arguments (Rodriguez and Silva 2007, Riera 2005). Firstly because of the existence of some lack of communication between different scientific areas of knowledge, which explains that those technicians with scientific formation different from economics that usually design prevention and combat strategies, are not able to apply or even simply to understand how and where economic tools can be used to meliorate the forest fire combat. Secondly, economic approach to these matters is particularly data consuming, as a large bundle of variables in number and different type and nature is

generally involved in the management process. However problems of scarcity and budget constraints one referred to earlier, points clearly to the direction of the increasing necessity of introducing economic thought into the process, in order to obtain more productive and efficient management of forest fires. To respond to these necessities, economic scientists have been developing empirical studies in order to use economic tools in the design and implementation of efficient and costless prevention and combat management forest fire strategies (Kline 2004, Riera and Mogas 2004, Rodriguez and Silva 2004, Loomis et al 2003, Prestemon et al 2001, Cleaves et al 2000).

In this paper, one wants to contribute to clarify how economic tools can be used to improve wildfire management planning to reduce fire risk and damages within a context of financial scarcity and highly probable raise of forest fire risk. We'll begin by defining and clarifying the concept of wildfire risk economic cost because this is the main objective of forest fire prevention and combat strategies (section 2). It will be shown this concept has two components, one associated with a high level of uncertainty, and the other associated with the level of destruction and/or damages. Further, we'll describe how the producer theory (section 3) can be used along with linear programming techniques in order to choose the better and cheaper way to combat wildfires, per each wildfire type. To operationalize these economic tools, sufficient data must be gathered in order to measure efficiently the variables involved by using geographic information systems – GIS – along with computer simulator programs (section 4). Finally Conclusions will be drawn.

## **2. Hazard and fury: “les bêtes noires” of a fire combat strategy planner**

As we outlined above, wildfire have three main characteristics that strongly affect and condition any type of management exercise. Firstly, these events are largely destructive and rapidly spread out of control. Secondly they characterize by high levels of destruction imposing to society a great financial burden, due not only to damages on properties and build infra-structures, but on human health and ecosystem related damages as well. And thirdly, wildfires have a strong component of uncertainty which is measured in terms of the probability of ignition and the probability of existing conditions to the development of the fire.

These three characteristics turn any attempt to manage fire combat strategies in an efficient way, into a very rough exercise. To manage efficiently the combat of a wildfire it is necessary to predict and detect locally its occurrence, to predict the way and the intensity of the fire spreading, and to predict as well the associated damages. The monetary value of potential damages when a fire occurs configures a very important type of information for administrations in order to help them to decide to what extent it will be socially and financially relevant to spend scarce resources in fire combats. Then, it is necessary to choose the better combination of resources to be used in the fire combat that must be the most productive and the costless one.

Wildfire occurrences are uncertain and depend of two factors: the probability of existing ignitions and the existence of previous conditions that favors fire development. Ignitions may have a human or a non-human origin, although humans are the more common. In Portugal 98,8% of the ignitions are caused by humans, of which 35,4% are non-intentional, 27,4% are unknown, and 26,8% are caused by human negligence (DGRF

2006). It is difficult to estimate the probability of ignition occurrences because the set of possible causes is very large. Some authors like Bachmann and Algöwer (1998) defend that this type of probability will rise with the degree of geographic spreading of human activities: the greater the number and intensity of human activities, the greater the probability of the occurrence of ignitions. The previous conditions that favor fire development are basically related with the quantity and the quality of the existent fuel on the terrain. To less fuel corresponds a smaller opportunity to fire development.

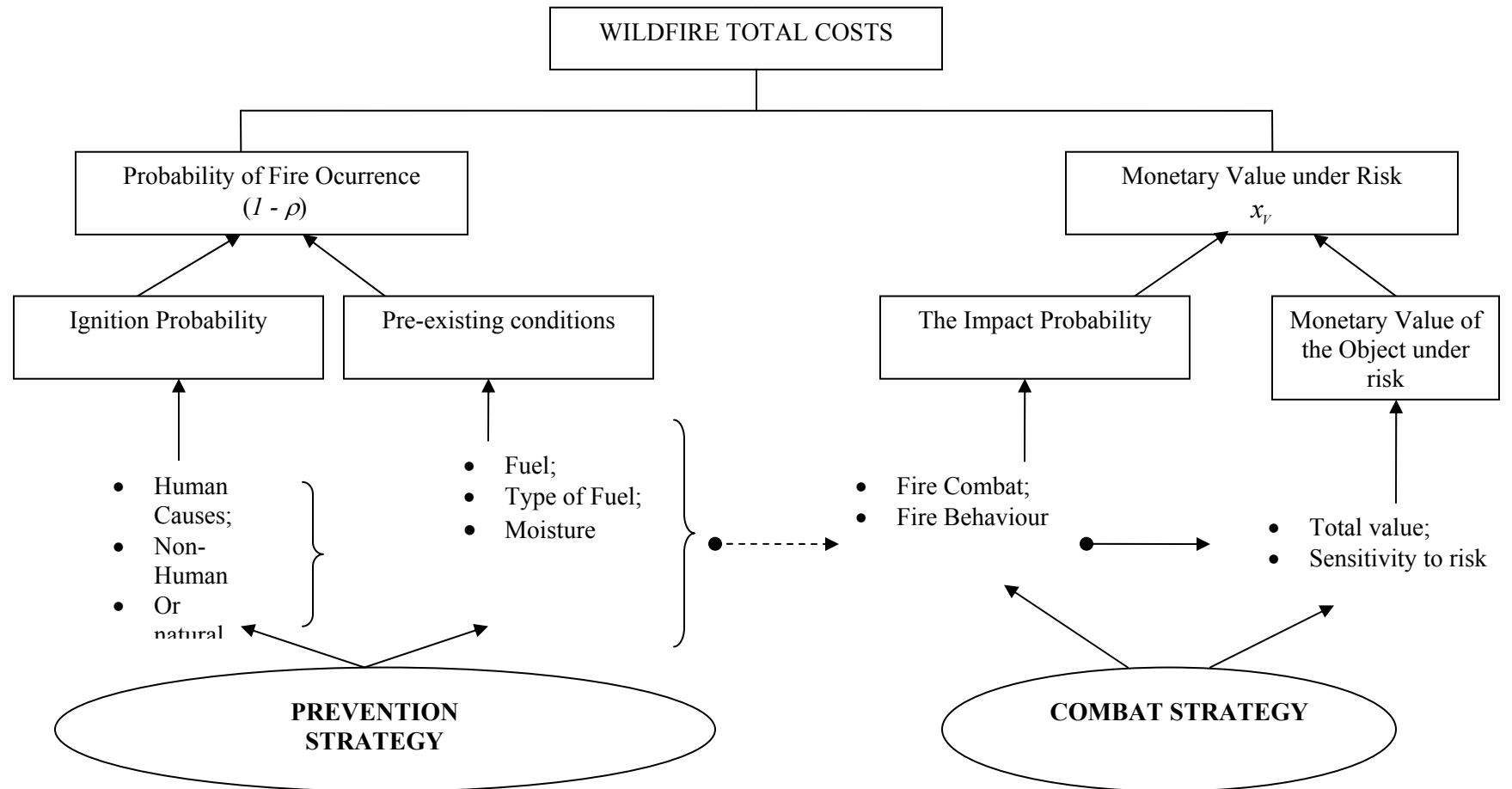
The risk of monetary value damages associated with the development of wildfires is clearly related with the probability of something be destroyed by a fire (the so called probability impact) and the monetary value under risk. Accordingly to Bachmann and Algöwer (1999), the impact probability depends on the way the fire spreads geographically. The fire spreading speed depends, in his turn, on the existent fire combat and prevention strategies and on the behaviour of the fire itself. The only way to decrease the number and the intensity of wildfires and to reduce the monetary damages as well, - which is equivalent to diminish the wildfire risk - is to implement and/or improve prevention and combat actions. The main goal of prevention and combat actions is so to minimize the number of occurrences and the monetary value of the damages and losses (Bennetton et al 1997). The main factor risks that affect the fire intensity and the damages associated to it, are local geographic and climacteric characteristics, the nature and the quantity of fuel on the terrain, and the efficiency of the already existent strategy of prevention and combat (Mercer and Prestemon 2005; Prestemon et al 2001). It is evident that among all these, the fuel and the prevention and combat strategy are the factor risks over which it is easier and costless to intervene to decrease the risk of wildfire.

In *figure 1* are schematically represented the fire risk factors and the actions that have to be implemented to reduce it. It seems to be evident to the reader that fire risk expected value management is a notion that incorporates two levels of analysis. The first is the monetary values under risk, their geographical dispersion and the assessment of the existing risk factors that condition the fire occurrence probability. The second level of analysis is the design and the implementation of more productive and costless strategies to prevent and fight the wildfires, in order to reduce the level of both wildfire ignition and spreading probabilities. Therefore, if we take into account: *i)* there is a great number of prevention and combat actions with different types of productivity and different total operational costs too; *ii)* the set of factors that affects the number and the intensity of wildfires is large and very heterogeneous; and *iii)* society has to take efficient decisions under severe financial, human and environmental restrictions, it is therefore reasonable to conclude that:

- It is necessary to design several prevention/combat action scenarios to deal with the imperative of reduce wildfire risk and associated losses and damages;
- It is necessary to adopt economic methodologies to choose the more productive and costless fire combat strategy.



**Figure 1** Fire Risk Factors and Fire Risk Integrated Management Actions



Till very recently, prevention and combat strategies have been traditionally designed by technicians coming from other scientific areas, different from economics (Riedout and Ziesler 2004). The absence of economic thought within these areas of management has been evidence particularly till the last century, and such a situation can be partially explained by two major arguments (Rodriguez and Silva 2007, Riera 2005). Firstly because of the existence of some lack of communication between different scientific areas of knowledge, which explains that technicians that ordinarily design prevention and combat strategies, possessing scientific formation different from economics, are not able to apply or even simply to understand how and where economic tools can be used to improve the forest fire combat. Secondly, because economic approach to these matters is particularly data consuming, as a large bundle of variables in number, of different type and nature, is generally involved in the management process. However, problems such as scarcity and budget constraints outlined above, point clearly to the direction of the increasing necessity of introducing economic thought into the decision process, in order to obtain more productive and efficient management of forest fires. To respond to these necessities, economic scientists together with others with different scientific formation, have been developing theoretical and empirical studies in order to introduce economic decision and analyzing tools into the process of designing and implementing efficient and costless prevention and combat management forest fire strategies (Kline 2004, Riera and Mogas 2004, Rodriguez and Silva 2004, Loomis et al 2003, Prestemon et al 2001, Cleaves et al 2000).

### **3. The Fire Combat Production Decision Problem**

Following the microeconomic Producer Theory, wildfire forest combat can be seen as a production activity, whose output measured in physical units per unit of time (extinguish  $x$  hectares of burning hectares during a time period  $y$  or to design a fire controlled line of  $x$  meters during a time period  $y$ ) depends upon: firstly the type and the number of material and human inputs used to the accomplishment of the task, and secondly the way these inputs are combined. That is, the output achieved depends on the wildfire forest combat technology used. The main planning fire combat's problem is how to choose the adequate bundle of fire fighting inputs that must be at the same time the costless and the more technologically efficient. Theoretically such bundle will be compatible with an economic Pareto equilibrium, i.e., will maximize social well being, and there is no other bundle capable of improving even more general well being, without turning someone else worst.

### *The Wildfire Combat Production Function*

Let  $q$  be the output of the wildfire combat production function measured, for instance, in terms of number of extinct burning hectares per time period. Let  $(r_i, r_j)$  be the bundle of different  $r$  quantities of fire fighting inputs of type  $i$  ( $r_i$ ), and  $r$  quantities of fire fighting inputs of type  $j$  ( $r_j$ ). The fire combat planners combine the inputs per type and quantities to produce or to achieve the desired output. This process can be described by precise engineering formulas where how many inputs are to be combined with one another in the fire combat process can be exactly specified. The end product, the output, can then be expressed as a function of all the inputs used in the fire combat. That function is

expressed by an equation, the production function of fire combat, and it derives from the fire combat steps.

The basic assumption that economists make about production functions is that they are technologically efficient. This means that, when inputs (firemen, helicopters, firemen's cars, tools, and others) are combined to fight a fire of several hectares in a certain period of time, a particular combination of inputs is said to be technologically efficient to achieve a certain result if it is not possible to get the same result using less of an input or no more of any other input.

The general form of the production function of fire combat is given by:

$$q = q(r_i, r_j) \quad (1)$$

where (1) represents a fire fighting technology, defined as different types and quantities of fire fighting inputs  $(r_i, r_j)$  combined in a specific mathematical form (Cobb-Douglas Production Function, or CES Production Function for instance, or other specific mathematical type) to which several fire fighting outputs are associated: to rising input quantities used to combat fires corresponds rising levels of output.

The first derivative of the production function in order of both inputs -  $\frac{\partial q(r_i, r_j)}{\partial r_i, r_j} > 0$  - gives the Marginal Productivity of each input ( $MgP_{r_i, r_j}$ ). The  $MgP_{r_i, r_j}$  is the increment of number of hectares of fire extinguished associated to the unitary increment of the input  $i, j$  used in the fire combat and is a positive value, meaning that the number of extinguished

burning hectares will grow with the number of fire combat inputs used. The second derivative of the production function is a negative value -  $\frac{\partial^2 q(r_i, r_j)}{\partial r_i^2, r_j^2} < 0$  - which means that  $MgP_{r_i, r_j}$  will decreasingly rise, as more fire fighting inputs are added to combat a specific fire. These two properties of a production function are generally referred, within the production theory, to the law of diminishing returns. Accordingly to this it, the first units of fire combat inputs will have a higher productivity, measured in number of hectares extinguished; however, there is a specific degree of concentration of fire combat inputs on the terrain which, if exceeded, will generate diminishing increases of the fire fighting results instead of increasing or constant ones. This is equivalent to say that fire combat inputs have diminishing productivities. If the fire combat's input prices remain constant, the existence of diminishing returns signifies that fire combat total costs will increase exponentially while the fire costs saved as a result of the fire output combat will be lesser, if a “more forest fire/more fire combat inputs” strategy is adopted. As a consequence, society will support a rising financial burden associated with the inefficiency of an expensive fire combat policy.

If one divides the level of output given by the production function in (1) by the total quantity of each type of fire fighting input, the planner will get a measure of the average productivity of the inputs used, i.e., the planner will get the median productivity of each input -  $MeP_{r_i, r_j}$  - calculated by equations (2) and (3):

$$MeP_{r_i} = \frac{q(r_i, r_j)}{r_i} \quad (2) \quad ; \quad MeP_{r_j} = \frac{q(r_i, r_j)}{r_j} \quad (3)$$

The concept of fire fighting production function enables the planner to compare each of all the existing fire fighting technologies to the others, by using their technological efficiency as the main criterion of ranking, accordingly to the level of fire fighting outputs and the productivity of each of the inputs used.

If the planner wants to know, what and how much of fire fighting inputs may be used to get a specific level of fire fighting output, the isoquant is the answer. An isoquant is a line that represents the bundle of all  $(r_i, r_j)$  that can be used in fire fighting to get the specific level of fire fighting output  $\bar{q}$  one wants to achieve. If the planner wants to know what and how much of fire fighting inputs may be used to achieve several levels of fire fighting outputs, the isoquant map is the answer. The isoquant map is defined as the set of isoquants representing different previously defined levels of fire fighting outputs. Analytically, one can get the general formula of the isoquant map by setting equation (1) equal to some cardinal –  $k$  - that represents some level of fire fighting output one wants to get and then solving for the input  $r_j$ , like in equation (2):

$$q = q(r_i, r_j) = k \Leftrightarrow r_j = f(r_i, k) \quad (2)$$

where  $k$  represents the specific level of fire fighting output one wants to concretize.

In short terms, the map of isoquants is a common method used by economists to rank different type of fire fighting technologies accordingly to the level of outputs they generate. If the ranking process follows the three properties mentioned below:

- i) all the possible input combinations  $(r_i, r_j)$  may be ranked;

- ii) all the combinations are transitive, that is if combination A is preferred to combination B which is preferred to C's, then A is preferred to C;
- iii) combinations using more inputs are preferred to those using less inputs, because output will be smaller,

then, isoquants are said to be well behaved, which geometrically means that they can be represented by convex lines, as those shown in *figure 2*:

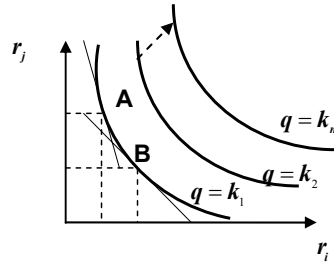


Figure 2 Fire Combat Isoquant Map

In *figure 2*, each isoquant represents a set of all combinations of fire combat input quantities that can be used, to achieve the same level of fire extinction,  $q = k_n$ . For example, the level of fire extinction  $q = k_1$  can be performed by using the combination of fire combat inputs A or B, or even any other, as long as it belongs to the isoquant  $q = k_1$ .

The property that isoquants are convex to the origin is referred to as diminishing marginal rates of technical substitution (MRST). Geometrically, this concept is defined as the negative of the slope of an isoquant and analytically as the ratio of the marginal product of the fire fighting inputs as given in (3):

$$MRTS = \frac{MgP_{r_i}}{MgP_{r_j}} = \frac{\frac{\partial q(r_i, r_j)}{\partial r_i}}{\frac{\partial q(r_i, r_j)}{\partial r_j}} \quad (3)$$

Diminishing MRTS economically implies that as  $r_i$  increases along an isoquant, the marginal product of  $r_i$  must decline relative to the marginal product of  $r_j$ .

By using the concept of fire fighting production function, the planner will also be able to compare the rhythm of variations of the quantities of all the inputs used in a fire combat with the correspondent rhythm of variations of the outputs. This particular relationship is designated by returns to scale, accordingly to the terminology of the production function theory, and is a long run concept<sup>1</sup>. As output expands in the long run, fire fighting production functions may exhibit the property of homogeneity. There are three types of homogeneous production functions. If doubling all the inputs exactly doubles, less than doubles, or more than doubles the output, we say the production function exhibits constant, decreasing, or increasing returns to scale - in other words, multiplying all the inputs by the same positive constant, multiplies output by the same constant, an inferior constant, or a greater constant. Analytically, the degree of homogeneity of the production function is known when one multiplies all the inputs of the production function in (1) by a positive constant  $\lambda$  such that:

$$q(\lambda r_i, \lambda r_j) = \lambda^\beta q(r_i, r_j)$$

The fire fighting production function has constant, increasing, or decreasing returns to scale if  $\beta = 1$ ,  $\beta > 1$ , or  $\beta < 1$ , respectively.

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<sup>1</sup> In the long run all inputs like the number of firemen or the number of fire combat vehicles vary. In the short run some inputs like firemen's quarters are fixed.



### *The Costs of wildfire combat*

Economists may estimate fire fighting production functions by observing choices of inputs used to combat wildfires on the terrain, and assuming that, to obtain a certain fire fighting output, planners always choose combinations of fire fighting inputs that are both technologically efficient and cost minimizing. The assumption that input's choices are cost minimizing for a given set of fire fighting outputs is referred to as an assumption of economic efficiency in contrast with the assumption of technological efficiency outlined above. Any input combination used to achieve a certain level of output is economically efficient, if it is not possible to produce that level of output at a lower cost, given the prevailing inputs prices. Given the inputs prices (bought in competitive markets) and setting the level of output to be achieved, the wildfire combat planner can use a wildfire combat production function to find the least-cost way of doing it.

To do so, first, the planner has to know the costs society has to support with wildfire combat. There are two main bundles of costs to be considered. The planner has to buy or rent the inputs necessary to combat a specific fire during a certain period of time, and the operational cost will simply be equal to the sum of the expenditures on each input. This is the first bundle of fire combat costs. If the planner wants to extinguish the fire within a small period of time, more inputs will be allocated, the higher will be the total operational cost of fire combat, and the less will be the number of hectares of forest burnt. Alternatively, if the planner wants to extinguish the fire within a greater period of time, less input will be allocated, total operational cost with fire combat will be lower but more hectares of forest will be burned.

The costs related with the hectares of forest meanwhile burned during the fire fighting combat, is the second bundle of fire combat costs the planner has to consider when assessing the overall costs of each fire combat strategy.

It seems evident that there is a clear trade-off between the costs of the inputs used in the fire combat and the costs supported by society related with the hectares of forest burned during the fire combat period. The more inputs are used, the more expensive the fire fighting strategy will be from the operational costs point of view, but the value of the losses in natural and built capital avoided will be higher. On the contrary, if planners, for the sake of budget restrictions, reduce the inputs used to fight a fire, the operational costs of the combat strategy will be less but the losses due to the fire will obviously rise. This means that the use of more inputs to fight a fire is not necessarily synonymous of raising costs to society, because they automatically will be compensated by the savings in terms of avoided damages.

Formally, let  $SRTC$  and  $LRTC$  be the short run and the long run total costs of a fire combat strategy respectively,  $VC$  the variable costs associated with the fire combat inputs whose value depends on the output  $q$ ,  $FC$  the fixed costs that do not depend of the output  $q$ . The total cost of some fire fighting strategy used to achieve a certain output  $q$  is given by (4) and (5) for the short and the long run respectively:

$$SRTC(q) = VC(q) + FC = p_i r_i(q) + p_i \bar{r}_j + c(1 - q) \quad (4)$$

$$LRTC(q) = p_i r_i(q) + p_j r_j(q) + c(1 - q) \quad (5)$$

where  $\bar{r}_j$  is the input that does not vary in the short run,  $p_i$  and  $p_j$  the prices of the inputs,  $c$  is the value of damages per each hectare of forest burnt, and  $(1 - q)$  is the hectares of forest lost during the fire fighting.

By dividing (4) and (5) by  $q$ , the average cost ( $ASRC(q)$  and  $ALRC(q)$  for the short and the long run respectively) of each additional hectare of fire extinguished, per fire, will be known. This information is given by equations (6) and (7), respectively for the short and the long run.

$$ASRC(q) = \frac{SRTC(q)}{q} = \frac{VC(q) + FC}{q} = \frac{p_i r_i(q) + p_i \bar{r}_j + c(1 - q)}{q} \quad (6)$$

$$ALRC(q) = \frac{LRTC(q)}{q} = \frac{p_i r_i(q) + p_j r_j(q) + c(1 - q)}{q} \quad (7)$$

It is also possible to know the total cost of each additional hectare of fire extinguished per period of time, or the marginal cost of  $q$  ( $MSRC(q)$  and  $MLRC(q)$  respectively, for the short and the long run), by taking the derivative of (4) and (5) in order to  $q$ . The results are given in (8) and (9).

$$MSRC(q) = \frac{\partial [p_i r_i(q) + p_i \bar{r}_j + c(1 - q)]}{\partial q} = \frac{\partial VC(q)}{\partial q} - c \quad (8)$$

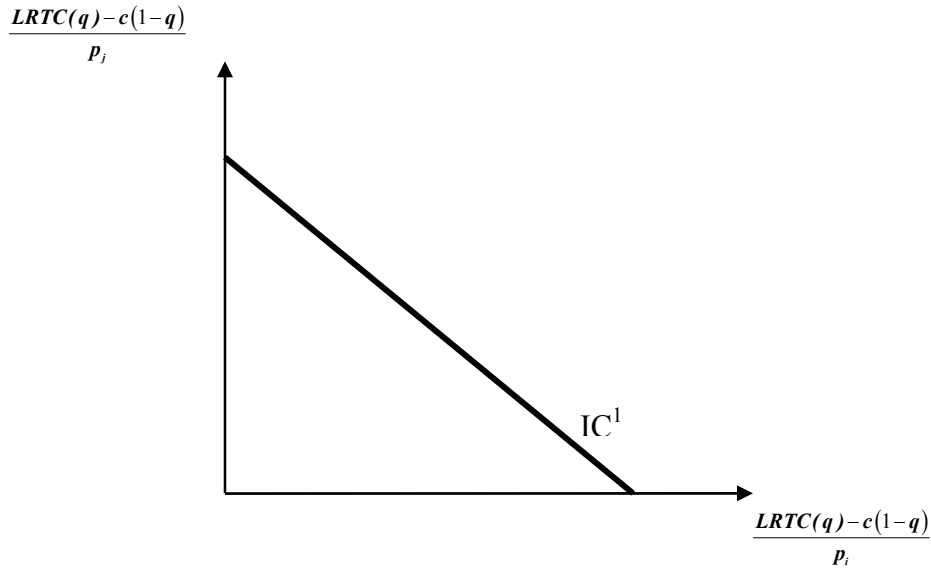
$$MLRC(q) = \frac{\partial [LRTC(q)]}{q} = \frac{\partial [p_i r_i(q) + p_j r_j(q) + c(1 - q)]}{q} = \frac{p_i \partial [r_i(q)]}{\partial q} + \frac{p_j \partial [r_j(q)]}{\partial q} - c \quad (9)$$

By (8) and (9) one concludes that the additional cost of one more hectare of fire extinguished per period of time has two components: one positive related with the cost of the additional units of input fire combat, and the other, negative, related with the damages saved by extinguishing one more hectare of fire.

Holding TC and the input prices fixed and varying  $r_i$  and  $r_j$  to satisfy the equation (5) tells the planner all the combinations of inputs that can be hired for a certain total cost of fire combat given the prices of the inputs,  $p_i$  and  $p_j$ . All these input combinations are given by a linear equation called the isocost line. Analytically, the isocost line is obtained by resolving equation (5) in order to  $r_j$  as given in (10):

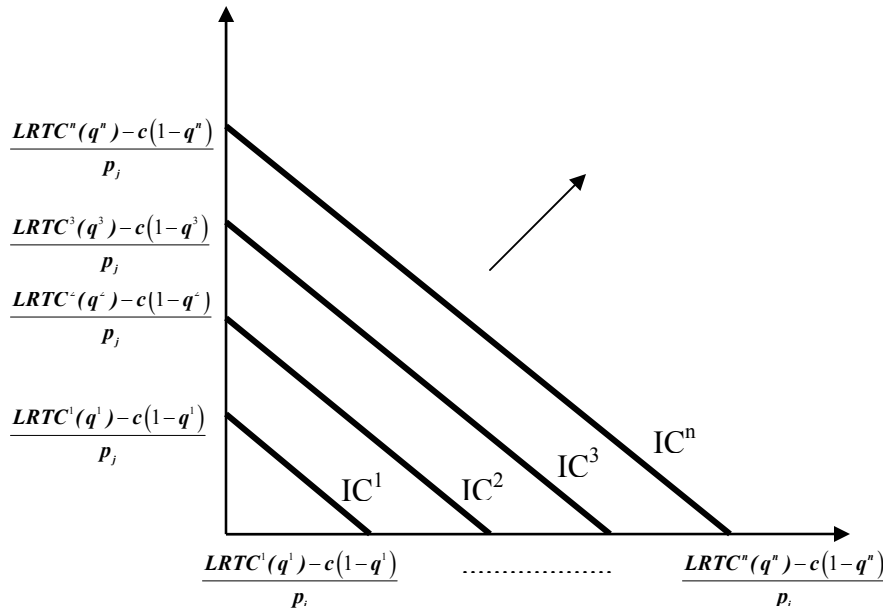
$$r_j(q) = \frac{LRTC(q) - c(1-q)}{p_j} - \frac{p_i}{p_j} r_i(q) \quad (10)$$

The line (10) is a linear function and can be represented in a  $r_i - r_j$  graph as illustrated in Figure 3.



**Figura 3** An Isocost Line

The slope of this line is the negative of the ratio prices  $-\frac{p_i}{p_j}$  and gives the opportunity cost of using one more unit of input  $r_i$  measured in terms of the decreasing of the use of the other input  $r_j$ , in order to maintain the same level of  $LRTC(q)$ . The intercept is  $\frac{LRTC(q) - c(1-q)}{p_j}$ . If  $LRTC(q)$  assumes different values, it is possible to estimate several isocost lines ( $IC^1, IC^2, \dots, IC^n$ ) as given in *figure 4*. Each of the IC lines represents all the combinations of inputs of fire combat that it is possible to make, given the input prices prices, that cost the same.



**Figure 4** A Map of Isocost Lines

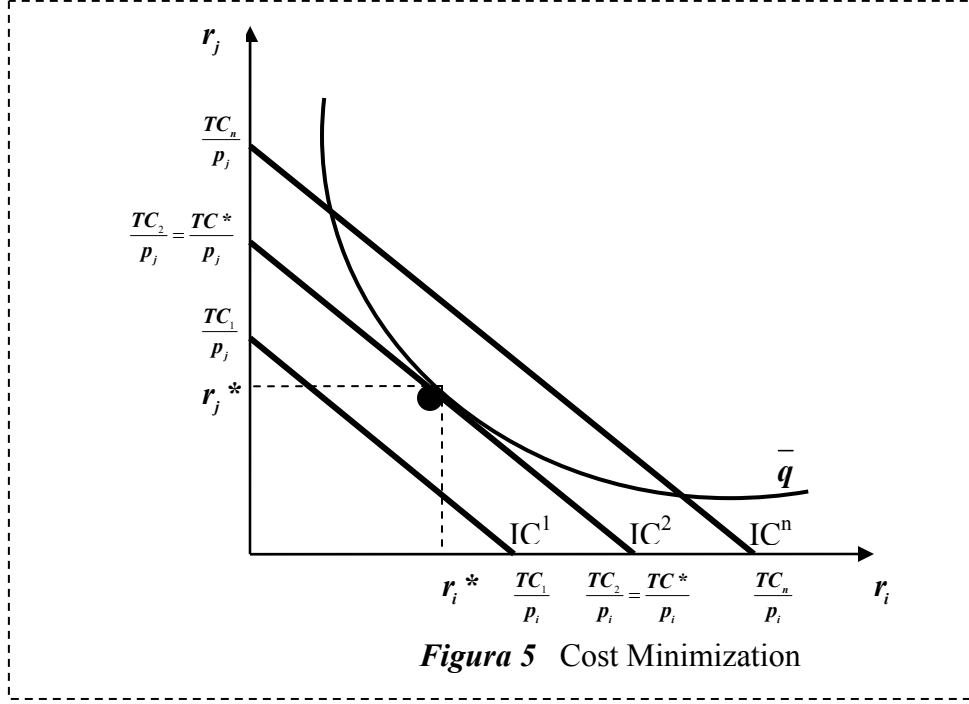
The arrow in *figure 4* indicates the trajectory of dislocation of the IC lines and of the total costs of combating wildfires, as more inputs are allocated.  $IC^n$  represents the input combinations that are more expensive and that corresponds to the same level of total cost  $-LRTC^n$ , while  $IC^1$  represents the costless combinations corresponding to  $LRTC^1$ .

### *Choosing the more efficient combination of fire combat inputs*

The problem of knowing what, from the economic point of view, is the more efficient combination of fire fighting inputs to combat fires, is similar to the problem of choosing the input combination that is more technologically efficient (the more productive), and the costless as well.

As outlined above, wildfire production functions represent sets of technologically efficient bundles of fire combat inputs; cost functions represent the total costs society has to support with the use of those sets of bundles, for every level of fire fighting achievement. To choose the more efficient input combination is similar to choose the more technologically efficient input bundle and the costless as well, to achieve a predetermined level of fire fighting output. This is the so called cost minimization problem. If we assume that the planner has a fire fighting production function that can be described by isoquant lines convex to the origin as those outlined in *figure 1*, and that fire fighting input market prices are parameters in the planner's decision problem, the minimization cost problem for each level of fire fighting output is resolved every time the fire combat planner adjusts its fire combat inputs mix until the technologically determined marginal rate of technical substitution equals the predetermined price ratio for those inputs.

The cost-minimizing fire combat input combination  $(r_i^*, r_j^*)$  for a predetermined fire combat output  $\bar{q}$  is geometrically founded at the point of tangency between the isoquant  $\bar{q}$  and the isocost line at TC\* (figure 5). This tangency condition can be interpreted as follows:



$$\text{slope of isoquant} = \frac{dr_j}{dr_i} = -\frac{p_i}{p_j} = \text{slope of iso cost line}$$

or

$$MRST = -\frac{dr_j}{dr_i} = \frac{p_i}{p_j} = \frac{MgP_i}{MgP_j} \quad (11)$$

Equation (11) summarizes the cost-minimization condition, and can be viewed as the rule of thumb for optimal choice of fire fighting inputs, both from the technological and the economical points of view, in order to achieve a predetermined fire combat result.

Analytically, the optimal bundle choice  $(r_i^*, r_j^*)$  is the solution of the minimizing cost problem outlined bellow:

$$\begin{aligned}
& \min_{(r_i^*, r_j^*)} p_i r_i + p_j r_j + c(1-q) \\
& \text{subject to } q(r_i, r_j) = \bar{q}
\end{aligned} \tag{12}$$

where  $q(r_i, r_j)$  is the fire fighting production function, specified by a function that better describes the engineering process of a fire combat;  $\bar{q}$  is the level of fire combat output to be achieved and is predetermined; and  $p_i r_i + p_j r_j + c(1-q)$  is the cost of doing it. We wish to minimize the cost of producing  $\bar{q}$ , given the prices of the fire combat inputs  $\bar{p}_i$  and  $\bar{p}_j$ . By using optimal programming techniques, the summarized first-order conditions for this problem are:

$$\begin{cases} \frac{MgP_i}{MgP_j} = \frac{p_i}{p_j} \\ q(r_i, r_j) = \bar{q} \end{cases} \tag{13}$$

$$\tag{14}$$

where (13) is the cost-minimization condition given in (11) and (14) is the technological restriction or the fire fighting production function. Solving the system above in order to the objective variables  $(r_i, r_j)$ :

$$\begin{aligned}
r_i^* &= f_i(p_i, p_j, \bar{q}) \\
r_j^* &= f_j(p_i, p_j, \bar{q})
\end{aligned} \tag{15}$$

The equations (15) are the solution of the cost-minimization problem (12), and they represent the optimal choice of  $r_i$  and  $r_j$  to achieve  $\bar{q}$ , both from the technical and the economical points of view. These optimal choices are represented by functions  $f_{i,j}$  called input conditioned demand functions. These functions mean that the optimal level of



$(r_i^*, r_j^*)$  to combat a fire, is dependent of the market prices of the inputs used to fight the fires and of the type of combat (the technology) as well.

Substituting (15) in the objective function in (12), we obtain the minimum cost of producing  $\bar{q}$ , given the input prices and the technological restrictions to combat the fire.

If we want to know the minimum cost of achieving different levels of  $\bar{q}$ , we only have to change those levels in (12).

#### **4. Applying the Fire Combat Production Decision Problem: the Use of GIS and Simulator Programs**

In practical terms, some countries have been evaluating their wildfire combat programmes by using methodologies with a theoretical structure similar to the outlined above: they are based on marginal analysis, linear programming and the estimation of functions. In practice, these tools reveal to be very useful to implement the task of planning efficiently the wildfire combat strategy, particularly within a backdrop scenario of accruing hazard, rising costs, and budget restrictions.

There is, however, a magna problem concerning the application of these methodologies: they are very data dependent. Not only extensive lists of different variables measured in physical as well as in monetary terms are necessary, but also simulations of wildfire behavior are an imperative to know the impacts that each of the fire combat inputs (evaluated either in isolation or in combination with others) has on the development of a specific wildfire. For instance, to estimate the fire fighting production function in order to assess the more productive input fire fighting techniques, within a predetermined period

of time a wildfire with specific characteristics, we have to simulate the wildfire behavior with and without intervention, to measure and quantify in physical terms the quantity of inputs used, and their productivity in terms of fire extinction as well. To estimate the cost functions of fire combats, not only data concerning the quantity of input resources used during the combat are necessary, but also the prices of the inputs and the monetary evaluation of the economic damages associated with wildfires are obligatory as well. Besides the data needs we just outlined, there is another important problem concerning specifically the monetary evaluation process of wildfire associated damages in terms of losses of natural, build, and human capital which constitutes, by itself, a difficult and very exigent task; this process is quite demandable in terms of data bases and in terms of the use of sophisticated technical evaluation methodologies (see more details in Mendes 2008). Rodriguez y Silva (2007) made an inventory of some of the data bases that, in his opinion, are obligatory:

- Identification of the geographical unit under analysis: natural protected area, hydrographic basin, forest stain, territorial administrative unit, region, country, etc;
- Data sufficient enough to characterize the geographical unit under analysis in geo-physical, climacteric and socio-economic terms, including inventories of all the natural, build, and human units of capital that it contains;
- Analysis of the wildfire behavior at the ignition phase, in the absence of intervention;
- Cartography of all type of existing fuels and of the forest and types of forest as well;

- Number of fires per year and per levels of intensity and duration;
- Wildfire speed propagation;
- Dimension in hectares of the surfaces affected at the moment of the ignitions;
- Historical of the incidents in geographical terms (by using GIS for instance);
- Historical of the climacteric conditions in median terms, per geographic units;
- Assessment of the potential losses and damages measured in physical and monetary terms, with and without fire combat;
- Data to plan the efficient use of resources in the fire combat: number and types of resources and productivity of the resources per types of fuel models;
- Data for the assessment and characterization of already existing fire system's detection and fire combat system;
- Data to evaluate the times of arrival of the resources of combat after the fire detection phase;
- Fire frequencies per type of intensity;
- Comparison between the speed of development of the fire control line and the speed of development of the fire perimeter;
- Operational costs associated with the combat interventions, per hectare;
- Number of fires with a development far beyond the expected;

By reading this list of data, one confirms immediately that the appliance of economic techniques to improve the fire combating planning decision and management process is particularly demandable in terms of data. But a closer look at the list, highlighted the idea

that data exclusively needed by economists and by no other technicians are those concerning the quantification of variables measured in monetary terms, particularly monetary costs of the resources used in combat and the monetary value of the damages and losses avoided with the intervention. All the others are data necessities common to economists and engineers as well. If this mix of physical and monetary data needed to assess fire risks, fire behavior, and the impacts of combat strategies, exists, economists will then be able to use their economic models to make efficient choices. In short, the active and effective participation of economists to meliorate the process of fire combat strategy planning is exclusively dependent on data; and these data can only be gathered by other technicians, but economists. This means that new wildfire combat integrated management strategies is an interdisciplinary exercise, which is the contrary of the planning fire combat processes that are more commonly put into practice (particularly in Portugal).

The main question one has to set now is to assess to what extent is it possible to get all this data. The answer can be found by analyzing the empirical experiences that have been put into practice by some countries. In the last few years some of the countries more exposed to this kind of natural disasters, and very aware of the huge monetary costs they provoke, have been developing and applying new integrated management practices based upon models that use economic decision techniques together with others, used to simulate wildfire behavior. Such models simulate the effects of the combat strategies per type of fire and per period of time of the extinguish phase. By combining several techniques like computer simulation programmes and GIS techniques, together with economic evaluation of losses and damages, these integrated models provide the

sufficient data bases that allows the choice of the more productive and costless fire combat resources in efficient terms, the integration of cost-benefit analysis, the modeling of the probability of the occurrences, and the evolution of line fires as well, with and without intervention.

Examples of these models include the Fire Protection Analysis (FPA) de 2003 applied in USA, the Level of Protection Analysis System (LEOPARDS) used in Canada, the Sistema Nacional para el Manejo de Incêndios Florestais (SINAMI) plus the program of economic analysis the ECOSINAMI used in Spain (these two were concluded at the end of 2006). Other examples of this integrated management models include the Fire Management Decision Support Systems (FFMDSS), KITRAL, California Fire Economics Simulation Model (FPPS/CFES), FirePro, ARMS/ADFF, ARCAR41, Rideout Model and Wildfire Initial Response Assessment System (WIRAS). All of these integrated models of planning use economic analysis methodologies to assess the value of the resources used to combat wildfires as well as the value of the losses and damages, to minimize the intervention costs and to choose the more productive combat fire strategies.

From the Portuguese point of view and in the absence of this type of integrated models, it is interesting to know in more detail the SINAMI and the ECOSINAMI models used in Spain because they were elaborated to resolve the specific problems of planning efficiently the wildfires combat concerning Mediterranean forest stains, which is a need common to the two Peninsula countries. Rodriguez y Silva (2007) describes shortly the SINAMI model and its potentialities. The model was elaborated to put into practice integrated management of Mediterranean forest stains, and combines the economic

analysis of the operational costs of wildfire prevention and combat measures and related productivity as well, with the economic valuation of wildfire associated damages and losses. Accordingly to Rodriguez *op. cit* the SINAMI allows: *i*) the identification of the more efficient sets of fire combat strategies (that is the fire production function, to use the theoretical lexical of *section 3*), per type of fire and per type of period of time (that is the fire production function, to use the theoretical lexical of *section 3*); *ii*) the simulation and measure of the productivity of human and non-human combat resources, used within the context of different scenarios of fire spreading designated as Fuel Models: to frame the scenarios and to define the Fuel Models, a GIS was applied to collect the necessary physical data to characterize the geographical unity under analysis in meteorological and topographic terms, as well as the type of local vegetation and its moisture level: to assess the productivity of the resources used in the fire combats per fuel model, computer simulations has been used; *iii*) allows to choose the costless and the more productive resources combination to built a controlled fire perimeter on one certain period of time that minimizes the economic fire damages and losses.

Some examples of data obtained from the SINAMI model are presented in the following tables. *Table 1* shows the productivity of different type of resources used in wildfire combat, per fuel model, measured in meters per minute. For instance, fuel model n°5 corresponds to the more common fuel combustion model in the geographical region under analysis and is characterized by dense and creeping bushes. With these data it is possible to measure the monetary operational costs of the combat strategies, per type of fuel model and to obtain the total cost functions of fire combat (see *section 3*). *Table 2* shows the number of hectares burnt and the perimeter of the controlled fire line, per each

**Table 1 Productivity of Fire Combat Resources**

Fuel Model	Firemen Brigades m/min	Extinguishing Groups m/min	Vehicles m/min	Bell 212 m/min	Tractor D6 m/min	Anfib Vehicle m/min	ACT802 m/min	Bell412 m/min
1	15	11	25	95	65	120	100	95
2	11	8	20	95	65	120	100	95
3	10	6	20	85	45	110	90	85
4	5	4	10	25	25	40	30	25
5	8	6	18	45	45	60	50	45
6	7	5	10	30	40	50	45	30
7	7	5	9	20	35	35	25	20
8	7	5	8	50	15	90	70	50
9	6	5	8	50	15	90	70	50
10	6	4	7	45	15	80	65	45
11	5	3	7	35	12	45	35	35

Font: Rodriguez y Silva (2007)

**Table 2 Number of Hectares Burnt and Perimeter of the Controlled Fire Line per Period of Time (Fuel Model n°5)**

Period of Time (hours)	Burnt Area (hectares)	Perimeter of the controlled fire line (meters)
2	92.3	4213.4
4	369.3	12 640.0
6	830.8	12 640.0
8	1477.0	16 853.5

Font: Rodriguez y Silva (2007)

period of time, for the fuel model n° 5. These numbers were obtained considering the more productive combination of combat resources chosen after the productivity results given in Table 1. Combining the information of tables 1 and 2 it is possible to know the more productive combination of combat resources, to extinguish a fire in a region characterized by a fuel model n° 5, per different periods of time. The results are in *Table 3*. With these data we could obtain the isoquanta map (see *section 3*) for the fuel model n° 5.

**Table 3 Combinations of Combat Resources (fuel model n° 5) Considering Four Time Periods**

Period of Time	2 hours	4 hours	6 hours	8 hours
Type of Resources Combination	1	1	3	4
Machinery	-	1	1	1
Specialist Group(7 persons)	1	1	-	1
Specialist Brigade (12 persons)	-	-	1	1
Water Vehicles	1	-	1	1
Semi-heavy helicopter Bell412 (transport and extinction)	-	-	-	1
Backing helicopter of transport and extinction	1	-	-	-
Semi-heavy load plane (AT-802)	-	-	1	-
Hydroplane (CL215T)	-	-	-	1
Operational Costs € (dislocation + extinction)	2539.24	1291.68	9789.30	22 778.51

Font: Rodriguez y Silva (2007)

Note that if we add to the operational costs of some combination of combat resources, the monetary costs of the hectares burnt during the combat, we obtain the total cost of fire combat (see *section 2*), per type of combat resources combination and period of time.

If we combine all these information accordingly to the algorithm described in the *section 3*, the planner will be able to choose the more efficient (that is the more productive and the costless) combination of resources to combat a fire in a particular local under specific fuel characteristics, per period of time.

### 3. Conclusion

Wildfires are characterized by high levels of destruction of build, natural, and human capital, imposing to Mediterranean society a great financial burden due not only to



damages on properties and build infra-structures, but human wealth and ecosystem related damages too. Wildfire occurrences are uncertain and they depend of two factors: the probability of existing ignitions and the existence of previous conditions that favors fire rushing. The only way to diminish the number and the intensity of wildfires and reduce the monetary damages is to implement prevention and combat actions.

Till very recently, prevention and combat strategies have been traditionally designed by technicians coming from other scientific areas, different from economics. The absence of economic thought within these areas of management has been evidence, particularly till the last century. However problems of scarcity and budget constraints point clearly to the direction of the increasing necessity of introducing economic thought into the process, in order to obtain more productive and efficient management of forest fires. To respond to these necessities, economic scientists have been developing theoretical and empirical studies in order to use economic tools in the design and implementation of efficient and costless prevention and combat management forest fire strategies. In this paper we describe how the microeconomic producer theory can be used along with linear programming techniques in order to choose the better and cheaper way to combat wildfires, per each wildfire type. We demonstrate and describe that economists have a theoretical methodology that can be useful in order to choose more efficient (meaning the more productive and the costless) strategies to combat wildfires, within a backdrop scenario of uncertainty. Further, we also demonstrate that this theoretical methodology may be fully put into practice if adequate data bases exist. However, the existence of these data bases is dependent of other technicians different from economists, which means that if administrations want to dispose of a more adequate operational

methodology to minimize the risk of wildfires, they will have to incentive the formation of multidisciplinary research teams.

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